OPTIMAL VOLTAGE STABILITY ASSESSMENT BASED ON VOLTAGE STABILITY INDICES AND ARTIFICIAL NEURAL NETWORK

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ABSTRACT

The evaluation of voltage stability assessment experiences sizeable anxiety in the safe operation of power systems, due to the complications of a strain power system. With the snowballing of power demand by the consumers and also the restricted amount of power sources, therefore, the system has to perform at its maximum proficiency. The noteworthy to discover the maximum ability boundary prior to voltage collapse should be undertaken. A preliminary warning can be perceived to evade the interruption of power system's capacity. This research considered the implementation of static and time-step system monitoring methods that able to provide a timely warning in the power system. Numerous types of line voltage stability indices (LVSI) are differentiated in this research to resolve their effectuality to determine the weakest lines for the power systems. The main motivation of these indices is used to predict and forecast the proximity towards voltage instability in the power system control and security applications. The indices are also able to decide the weakest load buses which are close to voltage collapse in the power system. Therefore, the static and time-step simulation (TSS) results are used to calculate the line stability indices and to ratify with voltage stability indices theory. The line voltage stability indices are assessed using the IEEE 9-Bus system, IEEE 14-Bus System and IEEE 30-Bus system to validate their practicability. The results are used to calculate the line stability indices by using Matlab software. This research also introduced the implementation of voltage stability monitoring by using Artificial Neural Network (ANN). Results demonstrated that the calculated indices and the estimated indices by using ANN are practically relevant in predicting the manifestation of voltage collapse in the system. Overall, VCPI(Power) index is able to detect the voltage collapse point precisely due to its accuracy in forecasting. This index successfully showed the capability to forecast the voltage collapse point either in small or a larger power system network. Therefore, essential actions can be taken by the operators in order to dodge voltage collapse incident from arising.

ABSTRAK

Penilaian taksiran kestabilan voltan mengalami pertimbangan yang kritikal dari segi aspek keselamantan dalam sistem kuasa elektrik. Dengan permintaan kuasa elektrik yang semakin meningkat daripada pihak pengguna dan jumlah penjanaan elektrik kuasa yang terhad. Maka, faktor-faktor ini menyebabkan sistem kuasa sentiasa beroperasi pada keadaan maksimum. Langkah perlaksanaan perlu ditekankan untuk mencari batas kemampuan maksimum sebelum keruntuhan voltan terjadi. Satu amaran awal mampu diperhatikan bagi mengelakkan gangguan kapasiti pada sistem kuasa elektrik. Kajian ini merangkumi pelaksanaan kaedah statik dan masa nyata dalam pemantauan sistem yang mampu memberikan amaran yang berkesan dalam sistem kuasa elektrik sebelum keruntuhan voltan terjadi. Pelbagai jenis indeks kestabilan voltan pada talian diaplikasikan dalam kajian ini untuk memantau keberkesanan mereka untuk menentukan talian yang tidak stabil pada sistem kuasa elektrik. Motivasi utama indeks digunapakaikan untuk meramalkan jarak ke arah ketidakstabilan voltan demi untuk mengawal sistem kuasa elektrik dalam aplikasi keselamatan. Sebaliknya, indeks juga mampu membuat keputusan untuk mengetahui beban *bus* yang paling lemah di mana dekat dengan kejatuhan voltan dalam sistem kuasa. Keputusan statik dan masa langkah simulasi telah digunakan untuk mengesahkan dengan teori kestabilan voltan yang sedia ada. Indeks kestabilan voltan talian dinilai menggunakan *IEEE 9-Bus*, *IEEE 14-Bus* dan *IEEE 30-Bus* untuk mengesahkan keberkesanan mereka. Kajian ini juga memperkenalkan pelaksanaan pemantauan kestabilan voltan dengan menggunakan *Artificial Neural Network (ANN)*. Keputusan menunjukkan bahawa indeks yang dikira dan indeks yang dianggarkan dengan menggunakan *ANN* adalah relevan untuk meramalkan keruntuhan voltan dalam sistem. Secara keseluruhan, indeks VCPI(Kuasa) mampu mengesan titik keruntuhan voltan dengan tepat kerana ketepatannya dalam ramalan. Oleh itu, tindakan-tindakan awal mampu dilaksanakan oleh pengendali untuk mengelak keruntuhan voltan insiden daripada mengambil tempat.

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LIST OF SYMBOLS AND ABBREVIATIONS

b	Bias for ANN
kV	Kilo Volts
I_L	Load Current
Z_L	Load Impedance
V_L	Load Voltage
J_R	Reduced Jacobian Matrix
θ	Teta
E_{TH}	Thevenin Voltage
w	Weight for ANN
Z_{TH}	Thevenin Impedance
AC	Alternating Current
ANN	Artificial Neural Networks
B	Shunt Charging
Degree	Bus Angle
FACTS	Flexible Alternating Current Transmission System
FFBPNN	Feed Forward Back Propagation Neural Network
FVSI	Fast Voltage Stability Index
GA	Genetic Algorithm

GW	Giga Watts
IEEE	Institute of Electrical and Electronic Engineering
LCPI	Line Collapse Proximity Index
Lmn	Line Stability Index
LQP	Line Stability Factor
LVSI	Line Voltage Stability Indices
MW	Mega Watts
P	Active Power
p.u	Per Unit
PMUs	Phasor Measurement Units
PSO	Particle Swarm Optimization
Q	Reactive Power
R	Series Resistance
RTDS	Real Time Digital Simulator
SI	Stability Index
TSO	Transmission System Operator
TSOs	Transmission System Operators
TSS	Time-Step Simulation
U.S.	United States
V	Volts
VCPI(Loss)	Voltage Collapse Point Indicators (Loss)
VCPI(Power)	Voltage Collapse Point Indicators (Power)

VSI	Voltage Stability Indices
WSCC	Western System Coordinating Council
X	Series Reactance

CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter is organised as subsequently. The background of the study will be reviewed in section 1.2. Problem statements for conducting this research are discussed in section 1.3. The main aim and objectives of the research are stated in section 1.4. The scopes of study for the research are outlined in section 1.5. The summary of the thesis outline will be described in section 1.6. Comprehensive summaries for Chapter 1 are justified in section 1.7.

1.2 Background of study

A number of blackouts interconnected to the voltage stability issue have happened in several countries. The greatest quantities of major blackouts took place in the year 2003. The United States (U.S.) -Canada blackout took place on August 14, 2003. During the blackout, the estimated values of 50 million people were affected in eight U.S. states and two Canadian provinces. Approximately, 63 GW of loads were interrupted, which equals to 11% of the total serving load in the Eastern Interconnection of the North American system [1].

According to the reports [1-3], more than 400 transmission lines and 531 generating units at 261 power plants were tripped during the year 2003 major blackout in North America and Europe. On September 23, 2003, a major blackout took place in Southern Sweden and Eastern Denmark and had an impact on 2.4 million customers [2, 4]. Five days later on September 28, 2003, some other major blackouts began when a tree flashover caused the tripping of a major tie-line between Italy and Switzerland [5, 6].

Voltage instability is a non-linear phenomenon. The instability is indicated when the network is being fully utilised up until it crosses the maximum deliverable power limits. The pioneer motivations for transmission network improvements and enlargements are dependable considerations and the interconnection of new generation resources. Some economic criteria and environmental consideration should be taken into account and hence will cause the planning to be postponed [7]. The rapid increasing of implementation of renewable energy are prone to cause the transmission network to be more complicated and stressed, since these sources have a higher and random behaviour.

Deserved by voltage stability characteristics from 10 seconds up to a few minutes range of time periods [8], the stability of the stressed power system obliged to be monitored in real time so that appropriate counter measures can be implemented in a timely manner, or else the system will experience voltage instability and sooner will lead to voltage collapse.

Voltage stability can be classified to have a strong relation linked to the theory of maximum load ability of a transmission network. When consumption loading is getting high enough, then compulsory measures should be taken in order to reduce the tension of the transmission network [9, 10]. A major problem related to tracking the maximum loading of the transmission system is that the maximum loading is not a fixed quantity, but relatively relies on the generation and load patterns, network topology and the accessibility of variable resources [11]. All the mentioned factors can differ with time due to unexpected disturbances and scheduled maintenances.

1.3 Problem statement and motivation

At present, power systems need to adapt to the new situation since the actual scene no longer exists as it used to be. Due to the climate change throughout the world, it is expected to lead the electricity consuming demand to operate closely to the numbers of generated electricity [12, 13]. Besides that, aggressive business conditions have enforced electric utilities to fully make use of accessible resources. Moreover, current power systems are extremely loaded as compared to the past because of the arising demand, maximum economic advantages and the effectiveness of the available transmission capacity [14-16].

The sequence of incidents that caused the major blackout in the year 2003, the reasons for the blackouts were due to a shortage of reliable real-time data [1, 17]. Established decentralized way of operating systems by Transmission System Operators (TSOs) where each TSO take cares of its own control area and limited information to exchange, resulted in insufficient and delay response towards contingencies. Therefore, a real-time security assessment and control are needed to maintain the system security [17]. The significance of real-time data is to allow the operators to carry out important and practically preventive action to avoid cascading or else will lead the system to incorrect or delayed corrective actions and thus will give a chance of instability occurrence.

Voltage stability assessment and control are not considered as any new issue [18], but they have now attained special attentions to maintain the stability of the transmission networks in order to avoid recurrence of major blackouts as experienced by the particular countries. The power system can be classified in the voltage stability region if it can maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance [8, 19]. In order to be reliable, the power system must be stable as most of the time. The research works on voltage stability can be broken down into various approaches, but the estimation on the power system's distance towards voltage collapse can be very handy to the operators before they take any remedial actions [20, 21]. The details on the distance towards voltage instability can be obtained by using Voltage Stability Indices (VSI) [22].

Voltage stability analysis is still widely being implemented in the industries by calculating the P-V and Q-V curves at selected load buses [23]. Commonly these curves are created by a large number of load flows using conventional methods and models. However, these methods are time consuming and do not provide sufficient practical information towards the stability problems [24].

The number of power systems outages throughout the world up is being illustrated in Figure 1.1. From Figure 1.1, it shows a significant growth for the power systems outages from year 2008 up until the year 2013. The greatest numbers of power outages occurred was in the year 2013 with 3236 cases. Besides, it also shows the trend still expanding up until the year 2013. Therefore, remedial actions should be taken beforehand to evade power system outages the following years.

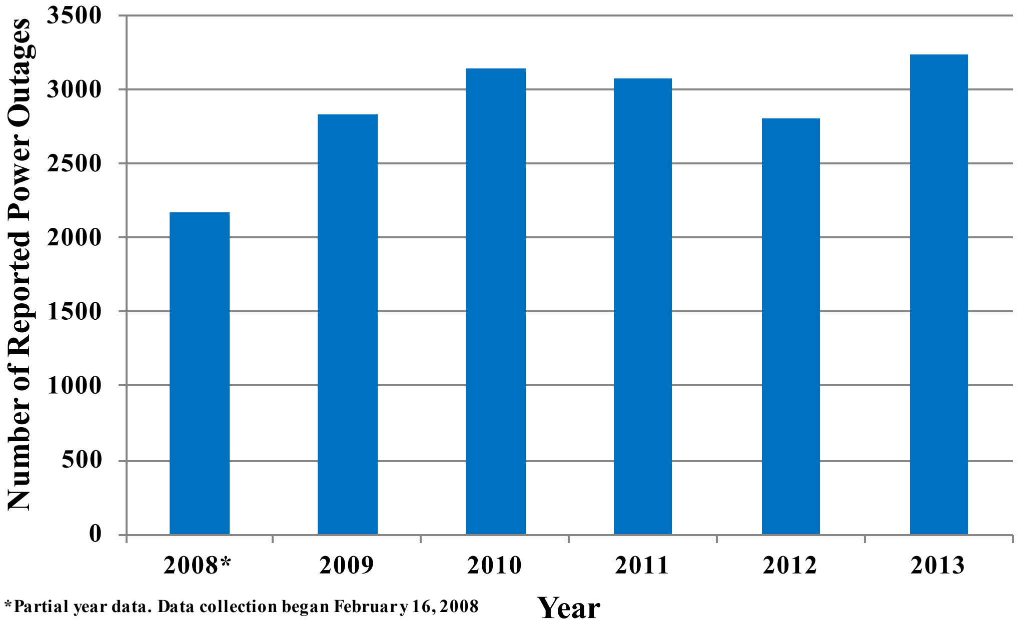

Figure 1.1: Total number of power systems outages in U.S. [25]

Various causes are recited in [26] as the commencement of the power systems outages. Most of all, power systems outages can be categorized into two types; unpreventable event and preventable event. Some of the power systems outages can be classified as the unpreventable events from the system operator. During the unpreventable event took place; the system operators are not in a position to control the damaged level happening in the power system.

In several other cases, the power system outages can be prevented with the utilisation of a sufficient system protection and situational awareness. If the power system is not equipped with suitable protection for the system, then the power system is prone to critical operational situations and leads to instabilities. Hence, voltage instability is one of the significant problems in causing the power outages.

1.4 Objectives of study

The main aim of this research was to validate the performances of line voltage stability indices to forecast the proximity of voltage instability in the power system. The following research objectives were conducted to achieve the principal aim of this research:

a) To describe, analyse and compare the reliability of the line voltage stability indices.

b) To demonstrate practical applicability of the conventional line voltage stability indices in the existing power systems.

c) To forecast the line voltage stability indices with the aids of artificial neural network for voltage stability monitoring purpose.

1.5 Research scope

Voltage stability indices can be classified into Jacobian matrix based voltage stability indices and system variable based voltage stability indices. In this research, the motive for focusing on the system variable based voltage stability indices is because it requires fewer amounts of computing time. Besides that, it can precisely verify the weak bus or lines in the power systems. Therefore, the scope has been narrowed into focusing on system variable based voltage stability indices.

All the power system calculations and simulation relative to the tests of the monitoring method are realised using grid software PowerWorld. PowerWorld is an interactive power system simulation package planned to simulate high voltage power system operation on a time frame ranging from several seconds to several days. The merits of the use of PowerWorld in this research are mainly the simulations of the variables of interest can be performed in phasors. Variable time step is well adapted for long-term occurrence identical to voltage instabilities.

Apart from that, the voltage stability analysis developed for the voltage stability monitoring is done by using Matlab® R2013a from the Mathworks Inc. The available phasors data generated by the PowerWorld simulator are saved in Microsoft Excel file format and then being imported into Matlab® by using the implemented algorithms.

Three test-power system cases are utilised all over in this research, which is IEEE 9-Bus test case, IEEE 14-Bus test case and IEEE 30-Bus test case. IEEE 9-Bus test case represents a portion of the Western System Coordinating Council (WSCC) 3-Machines 9-Bus system. This IEEE 9-Bus test case consists of three generators, nine buses and three loads. The IEEE 14-Bus test case actually represents a part of the American Electric Power System which is situated in the Midwestern US. This system consists of two generators, three units of synchronous condensers, 14 buses and 11 loads. On the other hand, IEEE 30-Bus test case represents a portion of the American Electric Power System (in the Midwestern US). IEEE 30-Bus test case consists of two units of generators, four units of synchronous condensers, 30 buses and 21 loads.

A two-layer feedforward back propagation neural network (FFBPNN) from the neural network toolbox in Matlab® R2013a from the Mathworks Inc is selected as part of the tool to determine the pattern of the data. The data is categorised in this application and FFBPNN is used to investigate the effects of power flow data in the power transmission line towards the line voltage stability indices.

1.6 Thesis outline

This thesis validates the performances of line voltage stability indices to forecast the proximity of voltage instability in the power system with the aids of artificial neural network. The literature studies of the relevant works are presented in Chapter 2. The literature studies of each proposed algorithm and methods are reviewed as well. Chapter 3 reviews the methods and approaches for the line voltage stability indices. Chapter 4 presents results and discussion for the implemented methods in forecasting the proximity of voltage instability for three different types of power system test cases. The predicted results for line voltage stability indices by using artificial neural network are illustrated in Chapter 4 as well. The conclusion and future works on the research are presented in Chapter 5.

1.7 Summary

This chapter discussed about the foreword for the entire research. The background of study associated with the research was explained in the section 1.2. The highlight in this section was about the overall characteristics of voltage stability. In section 1.2 also mentioned that voltage stability had a strong relation between the maximum load ability of a transmission network. The problem statement and motivation for this research were listed out in section 1.3. This section summarised the total number of power system outages in U.S from year 2008 up until 2013. The main intention of providing the statistic of power outages was to emphasise that the number of power outages still ongoing in the modern technology era. Therefore, remedial actions should be implemented in order to reduce the number of power outages for the following years. The main principle and objectives of the research were clarified in section 1.4. The main aim for this research was to validate the performances of line voltage stability indices to forecast the proximity of voltage instability in the power system. In order to achieve the principal aim in this research; therefore, three major objectives were achieved.

The research scope for the research was expounded in section 1.5. The brief summaries for the research scope were about the type of voltage stability indices, the implemented software in this research and the classification of the power system test cases that being executed in the research. The organisation of the thesis was evaluated in section 1.6. Overall, this thesis included five chapters.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter is managed in the following manner. Section 2.2 will discuss the brief introduction about the modern power system. In the meanwhile, section 2.3 will explain the overview for power system stability. The classification of power system stability will be presented in section 2.4. The definition and classification of voltage stability will be explained in section 2.5 and section 2.6 subsequently. The methods for voltage stability analysis will be elaborated in section 2.7. The overview of the voltage stability indices will be explained in section 2.8. The two different types of voltage stability indices will be discussed in section 2.9 and 2.10 respectively. The artificial neural network techniques in voltage stability monitoring will be explained in section 2.11.

2.2 Modern power system

Nowadays, the power system is an aggregate of interconnected network as illustrated in Figure 2.1. A power system can be partitioned into four prime parts:

a) Generation

b) Transmission and Subtransmission

c) Distribution

d) Loads

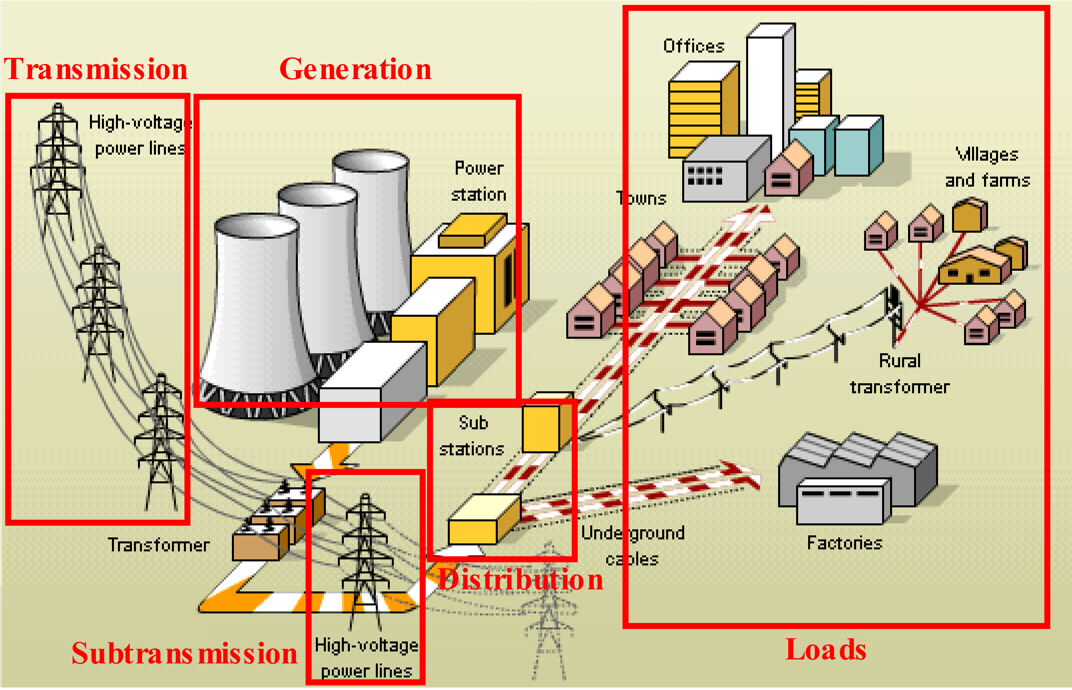

Figure 2.1: Basic components of a power system [27]

Various parts of the power system run at a different voltage rating. Commonly, the voltages are classified as low if they operate under 1 kV mark. Distribution systems ranging between 1 kV to 100 kV are classified as medium voltages. The voltages value from 100 kV to 300 kV are classified as high voltages and mostly located in subtransmission networks. Transmission networks that run above 300 kV are categorised as extra high voltages [28].

The generation part consists of generators. Three phase ac generator known as synchronous generator or alternator is the important component in the power systems. Today's systems use ac generators with rotating rectifiers, known as brushless excitation systems. The importance of a generator excitation system is used to maintain generator voltage and controls the reactive power flow. In a power plant, the size of generators can differ from 50 MW to 1500 MW.

Electricity is supplied by transforming the mechanical energy existing on the output shaft of an engine or a turbine into electrical energy. An external mechanical power source, commonly known as the prime mover is used to drive the synchronous generator. The prime mover's energy comes from various forms such as, hydraulic turbines at waterfalls, steam turbines whose energy is produced by burning coal, gas and nuclear fuel, gas turbine, or sometimes internal combustion engines burning oil [29].

Transmission is also significant in the power system. The main intention of an overhead transmission network is used to deliver electric energy from the generating units to the distribution system which is mainly supplied to the loads. The electrical energy lost in a transmission line is proportional to the current squared; therefore, most of the transmission lines perform at high or very high voltages. High voltage transmission lines are terminated in a high-voltage substation, receiving substations or primary substations. At the primary substations, the voltage is stepped down to a suitable value for the next part of the journey toward the load [8].

The section of a transmission system that connects the high-voltage substations through step-down transformers to the distribution substation is known as subtransmission network. Normally, the subtransmission voltage level ranges from 69 to 138 kV [30].

The distribution system is the part that connects the distribution substations to the consumers. Almost all electrical energy is delivered from the transmission or subtransmission network to distribution high voltage and medium voltage networks in order to supply straight to the consumers. The ratings for the primary distribution lines are from 4 to 34.5 kV. Some small industrial companies are served directly by the primary distribution lines. The secondary distribution network reduces the voltage for commercial and residential consumers. The secondary distribution mainly serves the consumers at levels of 240 V single-phase, three-wire and 415 V three-phase, four-wire.

Loads of power systems can be divided into industrial, commercial and residential. Industrial loads are combined loads and mainly consist of induction motors. The commercial and residential loads consist largely of lighting, heating and cooling. The demand for electrical power is never persistent and varies throughout the day and night.

2.3 Power system stability overview

Power system can be classified as a network that is connected to one or more generating units, power transmission lines and loads. Power system also consists of related equipment such as transformers and protective devices that are connected to it as well [31]. The suggested denotation in [32] for power system stability is the capability of an electric power system, for a specified starting operating condition, to recover a state of operating balance after being exposed to a physical disturbance, with most system variables required so that practically the whole system remains complete.

2.4 Classification of power system stability

Prior to further description of voltage stability, a documented definition of power system stability obliges to be described in order to obtain a clearer outlook. Typically, a recent power system is a high-order multivariable operation whose dynamic response is affected by a wide array of devices with various natures and response rate. Initially, the power system stability is a single problem but due to different forms of instabilities that the power system possibly experiences; therefore, there is a necessity to classify the power system into appropriate categories [8, 31].

The categorisation of power system stability is encapsulated in Figure 2.2. In accordance with Figure 2.2, power system stability can be classified into three system variables, which are rotor angle stability, frequency stability and voltage stability. The scale of the disturbance can also be divided into two categories, which are either small or large scale. The time duration of the disturbances can be classified into short or long term.

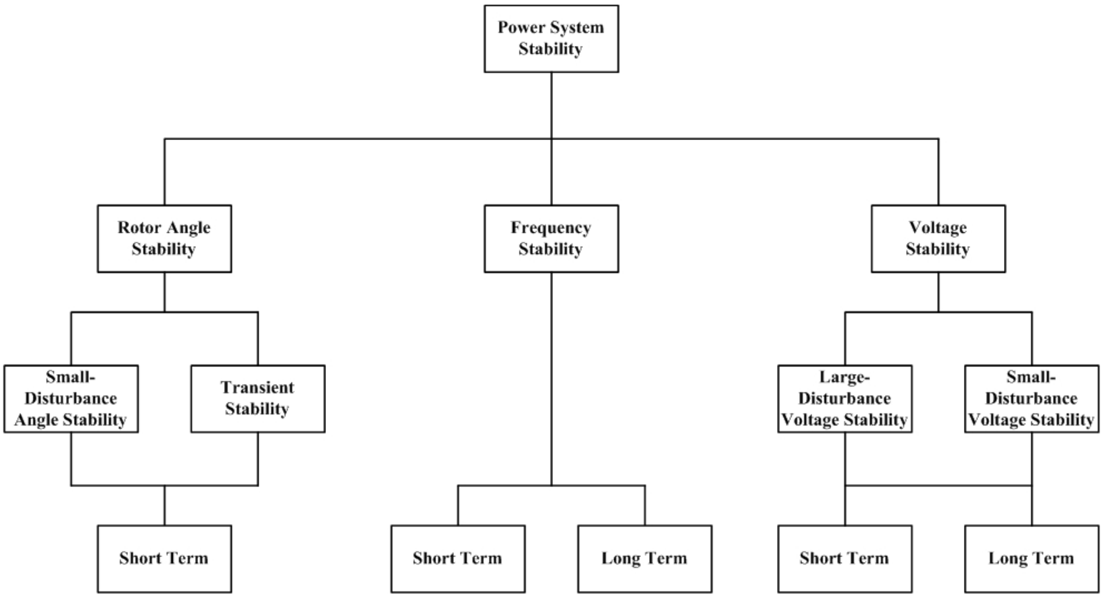

Figure 2.2: Categorisation of power system stability [8]

Rotor angle stability denotes the capability of the synchronous machines of an interconnected power system to endure in synchronism after being exposed to a disturbance. It relies on the ability to maintain or reinstate balance between electromagnetic torque and mechanical torque of each synchronous machine in the system. Rotor angle instability will result in the phenomenon of increasing angular swings of some generators and result in losing synchronism with other generators [8].

Frequency stability refers to the ability of the power system to preserve steady frequency upcoming a few system distress resulting in a notable imbalance between generation and load. The frequency instability may occur in the form of continuous frequency swings and will contribute to the tripping of generating units and/or loads [32].

2.5 Definitions of voltage stability

Voltage stability can be explained to the potential of the power system to sustain steady voltages at all buses in the system after being vulnerable to a disturbance from a given initial operating condition. Voltage stability is resultant on the ability of the power system to maintain or restore the equilibrium between the load demand and load supply [8, 32]. A system is considered as voltage instable if at least one bus in the system experiencing voltage magnitude decreases once the reactive power injection is rising [31].

During the occurrence of voltage instability, then the progressive fall or rise of voltages at some buses can be detected. The potential consequence of voltage instability is due to loss of load in the certain area, or tripping of transmission lines and other elements of the protection systems contributed to the cascading outages. Loss of synchronization for some generators may lead to the outages as well [33]. Voltage stability can also be considered as load stability. If the power system lacks of the capability to transfer an infinite amount of electrical power to the loads, hence voltage instability will be present. The main reason for contributing to voltage instability is the inability of the power system to meet the requirements for reactive power in the extremely stressed system keeping the desired voltages [34]. In order to restore the increasing demand of loads in the systems will cause further voltage decrement [32]. When there is at least one bus in the system encounter bus voltage decreases as the reactive power injection in the same bus is increased, and then the system is regarded as experiencing voltage instability.

Voltage collapse is the event when accompanied by voltage instability leads to a blackout or abnormally low voltage in a significant part of the power system [8, 35]. Due to the combination of events and system conditions, the additional reactive power demand may cause a voltage collapse, causing a major breakdown of part of all the systems.

2.6 Classification of voltage stability

Voltage instability and collapse effectively extent a time range from seconds to one hour. The time length of a distraction in a power system, originating a possibility of a voltage instability problem, can be categorised into short term and long term, which has been presented in Figure 2.3.

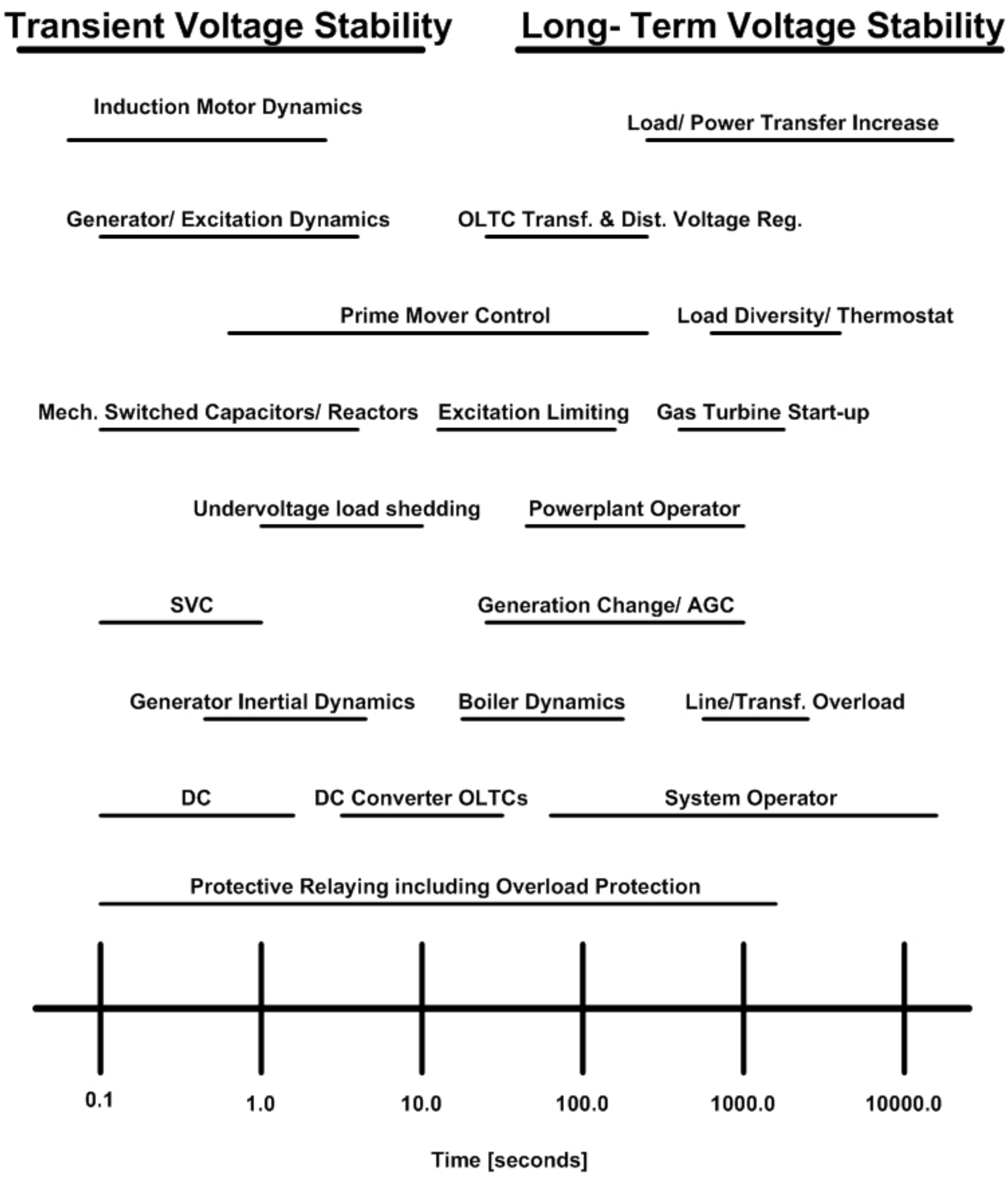

Figure 2.3: Time responses of different controls and components in voltage stability [8, 36, 37]

The time responses of different controls and components of voltage stability are presented in Figure 2.3. The example of short-term or transient voltage instability can be found mainly caused by rotor angle variance or loss of synchronism. In the meanwhile, long term voltage instability problems mainly occurred in heavily loaded systems where the electrical distance is huge between the generator and the load.

In order to analyse the voltage stability, it is often convenient to categorize the problem into small-disturbance and large-disturbance voltage stability. Small-disturbance voltage stability refers to the system's capability to continue steady voltages when disposed to small perturbations such as incremental changes in system load [8]. The analysis for small-disturbances is done in steady-state stability analysis. Steady-state stability analysis is useful in obtaining the qualitative overview of the system such as how stress the system is and the system's stability to the point of instability. Large-disturbance voltage stability refers to the system's ability to maintain stable voltages followed by large disturbances such as system faults, disappearance of generation and loss of line. Large-disturbance voltage stability can be analyzed by using non-linear time-domain simulation in short term time frame and load flow analysis in the long term time frame [34].

2.7 Methods for voltage stability analysis

Many different analytical methods have been proposed in the previous research works aiming to provide a better understanding of the phenomenon, to evaluate the systems in operating conditions, and to come up with appropriate control measures to keep systems from experiencing voltage instability situations. In organizing and performing power system scheme, the investigation of voltage stability can be associated with two different aspects [8, 38];

a) Proximity to voltage instability: How close is the system towards voltage instability?

b) Mechanism of voltage instability: During voltage instability occurs, what are the fundamental elements that contributing to instability? What are the weak voltage areas? What computational methods are most efficient in enhancing voltage stability?

Various aspects of voltage stability problems can be efficiently analyzed by using static methods [39]. These methods examined the viability of the equilibrium point represented by a specified operating condition of the power system. In voltage stability studies, the characteristics of interest are the relation between the transmitted power (P), receiving end voltage (V) and reactive power injection (Q). Traditional forms of displaying these relationships are P-V and Q-V curves obtained through steady-state analysis. Sensitivity analysis and modal analysis are also being used in voltage stability assessment to make use of system condition or snapshot for voltage stability evaluation [40].

2.7.1 Power flow analysis

Power flow analysis or load flow analysis is the main analytical tool being performed in large and complex power networks for reactive power resources planning purposes. The power flow analysis involves the calculative of power flows and voltages of a transmission network for a particular terminal or bus conditions. This computational is required for the analysis of steady-state as well as dynamic performance of a power system [8, 41].

For bus classification purpose, each bus is corresponding to four quantities which are active power P, reactive power Q, voltage magnitude V, and the voltage angle, θ. The following types of buses (nodes) are described and at each bus will consist of two of the four quantities.

a) Voltage-controlled (*PV*) bus: Active power and voltage magnitude are stated. This bus is limited to the reactive power and depends on the characteristics of the individual equipments. For examples are buses with generators, synchronous condensers, and static variable compensators.

b) Load (*PQ*) bus: Active power and reactive power are stated. Usually loads are considered to have constant power.

c) Slack (*Swing*) bus: Voltage magnitude and phase angle are specified. Due to the power losses in the system are unknown in earlier, therefore at least one bus must have unspecified P and Q. Thus, the slack bus is the only bus with known voltage.

The correlation between network bus (node) voltages and currents possibly represented by either loop equations or node equations [8, 41]. Node equations are preferred because the number of independent node equations is smaller than the number of independent in loop equations. The network equations in terms of the nodal admittance matrix can be written as in Equation 2.1.

$$\begin{bmatrix} \overline{I_1} \\ \overline{I_2} \\ \cdots \\ \overline{I_n} \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} \overline{V_1} \\ \overline{V_2} \\ \cdots \\ \overline{V_n} \end{bmatrix} \tag{2.1}$$

Where:

n is the total number of nodes

Y_{ii} is the self admittance of node i = sum of all the admittances terminating at node i

Y_{ij} is the mutual admittance between nodes i and j = negative of the sum of all admittances between nodes i and j

$\overline{V_i}$ is the phasor voltage to ground at node i

$\overline{I_i}$ is the phasor current flowing into the network at node i

Equation 2.1 would potentially be linear if the current injections $\bar{I}$ were known. However, in practical the current injections are unknown for most nodes. The current of any node k is related to P, Q and V can be represented in Equation 2.2.

$$\overline{I_k} = \frac{P_k - jQ_k}{\overline{V_k}^*} \tag{2.2}$$

The relations of P, Q, V and I are explained by the properties of the devices that connected to the nodes. Different type of properties will cause the problem to become nonlinear and therefore, power-flow equations are needed to be solved by using techniques such as the Gauss-Seidal or Newton-Raphson method [42, 43].

The Newton-Raphson method is the most popular method in finding the roots of non-linear equations [8]. The Newton-Raphson method has a very good convergence rate. The computational time increases only linearly with the size of the system. By using this method, the model can transform into linear equation and is provided in Equation 2.3.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \tag{2.3}$$

Where:

$\begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V} \end{bmatrix}$ is the Jacobian matrix

ΔP is the incremental change of real power injection at the bus

ΔQ is the incremental change of reactive power injection at the bus

$\Delta \theta$ is the incremental change of bus voltage angle

ΔV is the incremental change of bus voltage magnitude

2.7.2 Modal analysis

The modal analysis or known as eigenvalues analysis can be implemented as a systematic handy tool to identify both proximity and mechanism during the occurrence of voltage instability. This method necessitates the calculation of the small number of eigenvalues and associated eigenvectors of a reduced Jacobian matrix. The reduced Jacobian matrix is able to provide handy information about the voltage stability. Initially, system voltage stability is influenced by both P and Q. However, by utilising the reduced Jacobian matrix; the concern is mainly on the reactive power and voltage characteristics. By this, weak buses in the power system can be recognized from the system reactive power variation towards the incremental change in bus voltage magnitude [38].

Therefore, at each operating point, the P is being kept as constant and just assesses the voltage stability by considering the incremental relationship between Q and V. Therefore, the ΔP in Equation 2.3 is set to 0 and can be simplified as shown in Equation 2.4.

$$\Delta Q = J_R \times \Delta V \tag{2.4}$$

Where:

$$J_R = \left[J_{QV} - \left(J_{Q\theta} \, J_{P\theta}^{-1} \, J_{PV} \right) \right] \tag{2.5}$$

By referring to Equation 2.5, J_R is the reduced Jacobian matrix of the system. The matrix J_R is symbolised the linear relationship between the incremental change in bus reactive power injection, ΔQ and bus voltage, ΔV. Voltage stability characteristics of the system can be identified by computing the eigenvalues and eigenvectors of the reduced Jacobian matrix, J_R which being defined in Equation 2.5 [36, 38, 44, 45]. Thus, the smallest eigenvalues of J_R are considered as the least stable modes of the system.

2.7.3 P-V curve

P-V curve is beneficial for a conceptual analysis of voltage stability due to its simplicity. P-V curve is a traditional method used for illustrating the voltage instability phenomenon [46]. From a P-V curve, the difference of bus voltages with load, distance to instability and critical voltage when instability occurs may be resolved. However, it is not the most practical way to study the voltage stability since it requires a long computational time for a large complex network. The power flow simulation will diverge near the nose or maximum power point on the curve. Another disadvantage is that generation must be realistically rescheduled as the load area is increased. Most importantly, the relationship of voltage to active power transfer is non-linear, which requires the full power solutions.

2.7.4 Q-V curve

Q-V curve is used to indicate the sensitivity relation of bus voltages with respect to the reactive power injections. The Q-V curve can be used as an index for voltage instability. At the point of dQ/dV equal to 0 is the point of voltage stability limit. The typical theoretical Q-V curve is illustrated in Figure 2.4. One of the significant information that can be retrieved from the Q-V curve is the relation of sensitivity between the loads and the reactive power sources [47].

When adjacent generators attain their reactive power limits, the slope of the Q-V curve becomes less steep and the bottom of the curve is approached. The system is approaching instability condition when the nose tips of the graph approaching zero. With these advantages, Q-V curves are presenting a promising method of voltage stability analysis at many utilities.

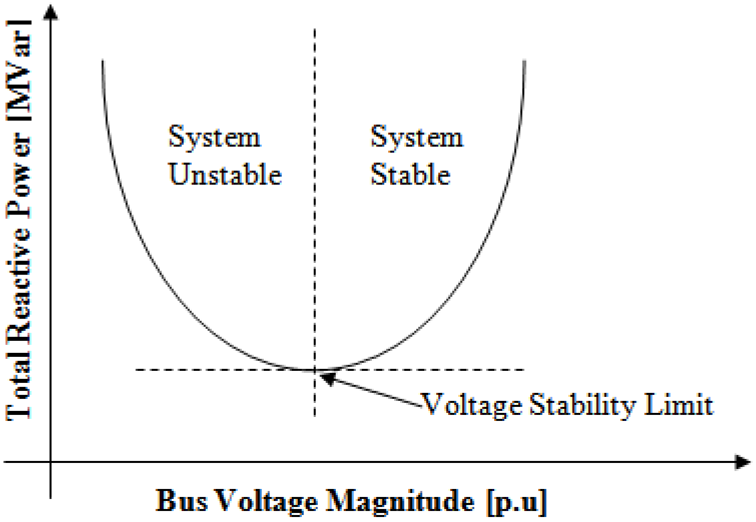

Figure 2.4: Typical theoretical Q-V curve [48]

2.7.5 Power transfer stability index based on the system Thevenin equivalent

A power transfer stability index is proposed in [49]. The stability indices presented consider the Thevenin equivalent of the power system connected to a load bus where an apparent load is connected. The concept used for the Thevenin equivalent network is presented in Figure 2.5. Based on Figure 2.5, the bus Z has a load demand on the right side. In the meanwhile, the Thevenin equivalent of the system (the rest of the power system) is connected to the left side of the bus Z.

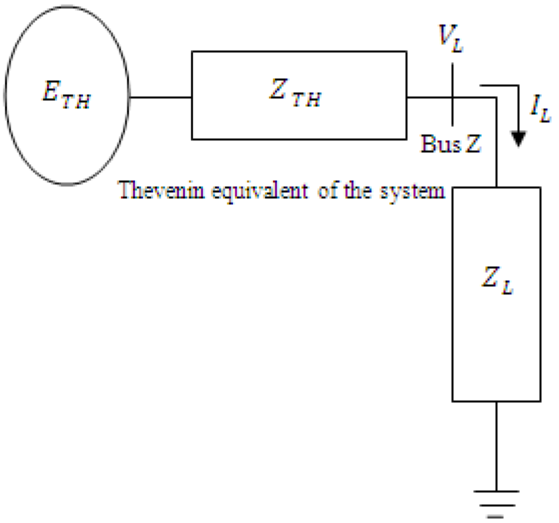

Figure 2.5: Thevenin equivalent network [21, 46]

The maximum load apparent power is also considered as the maximum load ability which depends on the Thevenin parameters varying the system operating conditions. The maximum power transfer is found when $|Z_L| = |Z_{TH}|$ [9, 10, 46, 50].

2.8 Voltage stability indices

Voltage stability indices are very applicable in retrieving the voltage stability of the power system. Voltage stability indices are the scalar magnitudes that are being implemented to observe the changes of the parameters of the system. Besides that, the indices are also used to quantify the distance of the particular operating point with the point of voltage collapse [51]. These indices will be very handy to the operators before they started to implement the preventive actions [21].

The main intention of this section is to provide a complete and wide viewpoint of the voltage stability indices. According to the articles in [52, 53], the authors mentioned that voltage stability indices particularly could be subdivided into two parts, which are Jacobian matrix based voltage stability indices and system variables based voltage stability indices.

Jacobian matrix based voltage stability indices are able to calculate the voltage collapse point or maximum load ability of the system and discover the voltage stability margin. However, these indices required high computational time and for this particular reason, the Jacobian matrix based voltage stability indices are not appropriate for online assessment. System variables based voltage stability indices required less computational time. The reasons are due to the system variable based voltage stability indices that used the elements of the admittance matrix and some system variables such as bus voltages or power flow through the lines. With the benefit of less computational time, system variables based voltage stability indices are suitable to be implemented on the online assessment and monitoring purposes. At the same time, system variables based voltage stability indices cannot efficiently estimate the margin because their responsibilities are more to determine the critical lines and buses.

The differentiation between Jacobian matrix based voltage stability indices and system variables based voltage stability indices is being catalogued in Table 2.1. The differentiation is more likely based on the two aspects which were being defined in [8]. The two aspects are proximity towards voltage collapse – (How close is the system to voltage instability?) and mechanism of voltage instability – (How and why does instability occur?).

Table 2.1: Differences between Jacobian matrix based voltage stability indices and system variables based voltage stability indices

Jacobian matrix based voltage stability indices	**System variables based voltage stability indices**
Require more amount of computing time	Require less amount of computing time
Suitable for offline monitoring purpose	Suitable for online monitoring purpose
Discover voltage stability margin (Proximity towards voltage collapse)	Discover weak buses and lines (Mechanism of voltage instability)

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